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Environmental concerns of underground coal gasification

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ABSTRACT

Underground Coal Gasification is the conversion of solid Coal to gas in-situ by heating the coal and injecting oxidants air/oxygen to cause the gasification by partial combustion instead of complete combustion of coal. UCG is the promising technology having a lot of health, safety and environmental advantages over the conventional mining techniques; the major motivational aspects of UCG involves increased worker health and safety by using no man underground, no surface disposal of ash and coal tailings, low dust and noise pollution, low water consumption, larger coal reserves exploitation, and low volatile organic components, methane and green house gases emission to atmosphere. UCG is an inherently clean coal technology as it reduces deadly sulfur and nitrogen oxide emissions to very low levels. Total solid waste from UCG is typically half the volume generated by conventional coal plants and water use is substantially lower as well.

Contents

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1. Introduction

Underground coal gasification (UCG), wherein coal is converted to gas in-situ, moves the process of coal gasification underground. Gas is produced and extracted through a pair or Grid wells drilled down into the coal seam, one well is used to inject air or oxygen to combust the coal in-situ which is known as injection well and second is used to extract the syngas to the surface for further processing known as production well. The process relies on the natural permeability of the coal seam to transmit gases to and from the combustion zone, or on enhanced permeability created through the reversed combustion linking (RCL) process, that provide an in-seam channel by high pressure air injection. Soon after the RCL completion the process of gasification starts. Gasification is done by the injection of low pressure high volume air. The syngas collected through production well then brought to purification plant. The syn gas can then be used in similar applications to natural gas, like producing electricity or as a chemical feedstock.

1.1. History of UCG

UCG was first conceived as early as 1868 by Sir William Siemens in Germany and independently by The Russian chemist Mendeleev in 1888. The UCG process technology was patented by the American Betts in 1909 and the first UCG field test program was carried out by Ramsey in England in1912. Lenin's interest in employing UCG to relieve the Russian workers from the drudgery and hazards of coal mining led to a major field test program in the Soviet Union in 1931. This effort led to the construction of three UCG commercial size UCG plants in Russia. Subsequent huge oil and natural gas discoveries in Russia and availability of cheap oil from Middle East curtailed UCG process development through the world until very recently. However, a few facilities continued to operate including one in Angren, Uzbekistan. The United States also experimented with the technology during the 1970s and 80s. Although interest in UCG waned at the end of the 1970s, there were still 30 pilot projects worldwide between 1975 and 1996 [1]. Increasing energy costs and energy demand have renewed global interest in the technology.

1.2. Advantages of UCG

The advantages of UCG relate to its recovery, chemical feedstock value, environmental impact, health and safety benefits, process efficiency and economic potential. It can be used to recover the energy content of low rank fossil fuels such as sub bituminous coals and lignite that are not economically or technically feasible to recover by the conventional technologies because of their seam thickness, depth, high ash and excessive moisture content, large dip angle, or undesirable overburden properties. It also may offer the only feasible technology for recovering the extensive offshore coal deposits.

Large area of the land are not removed from use for any long periods of time in UCG recovery as they would be in deep shaft or

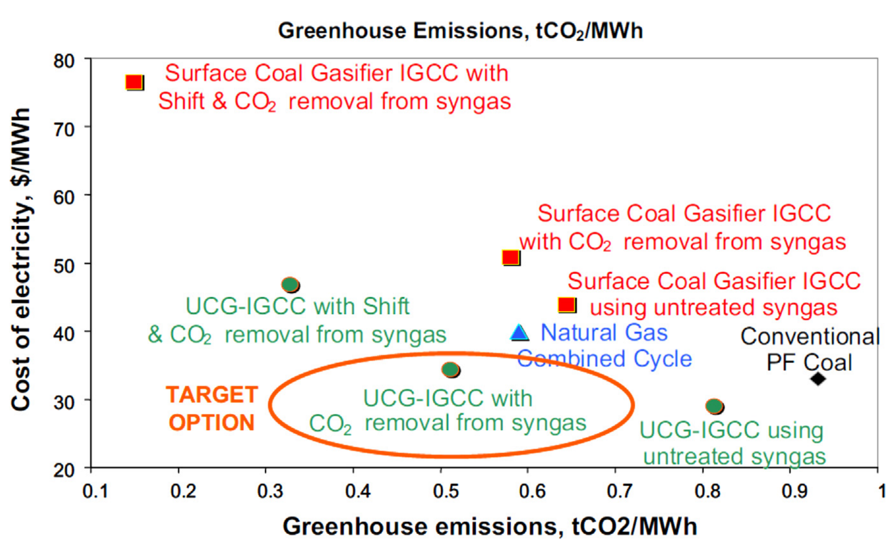


Fig. 1. Greenhouse emission.

strip mining. Reclamation of the land is not a serious problem since the surface disturbance is minimal. In particular, there is no solid waste disposal problem since all the ash remains underground. The UCG process also generates minimal atmospheric pollution, less surface disruption and sulfur appears in the coal as hydrogen sulfide rather than sulfur dioxide. It also uses less water than the surface gasification processes which must maintain a high steam-air ratio to avoid slagging. These environmental benefits as well as the fact that mining is avoided imply that the UCG offers corresponding health and safety advantages.

The UCG process has high thermal efficiency than surface gasification processes since it does not require high steam to air ratios and has substantially low heat losses due to insulating properties of overburden. Finally the capital investment costs for UCG are estimated to be 75 percent of those for surface gasification since it is not necessary to construct high pressure reaction vessels.

1.2.1. Low carbon emission electricity

By applying the UCG-CCS technology to suitable coal deposits, electricity can be produced at a similar cost to conventional coal power stations with half the greenhouse emissions.

Fig. 1 shows the Australian cost and greenhouse gas emissions for a range of new clean coal technologies compared to conventional pulverized fuel (PF) coal fired power stations and natural gas fueled generators. The upper square plots show the performance for surface coal gasification plants with three options, one using the gas directly from the Gasifier, second removing CO_2 from the gas before combusting it, and the third, most expensive 'zero' emission option, converting the gas to hydrogen and CO_2 and removing theCO_2 before combustion. The lower circle plots show the same three options for UCG gas. There is a 'sweet spot' with the second option which provides 50 percent reduction in CO_2 emissions with no increase in cost over current coal fired power stations [2].

Table 1
The output of the fully developed chinchilla project.

Product	Output	Energy
Electricity		67 MW
Gas	800 million Nm_3/annum	4.4 PJ/annum
Hydrocarbons	15,000 t/annum	0.6 PJ/annum
Phenols	3700 t/annum	–
Anhydrous NH_3	1500 t/annum	–
Clean water	200 Megaliters/annum	–

1.3. UCG: the environment friendly technology

The UCG process is the most environmentally friendly use of coal. Beyond the primary benefit of CO_2 capture and sequestration, UCG has several other environmental benefits over traditional coal extraction. By gasifying in-situ, there is no surface scarring or reclamation necessary; the UCG surface footprint is minimal and requires no surface dislocation. Meanwhile, the ash created in the process remains below ground alleviating disposal concern. Since the coal is not mined, the traditional mining equipment (trucks, scoops, etc.) and their associated emission are removed from the process. By not scarring our planet, creating waste ashes or involving heavy equipment, UCG is the cleanest of coal usage [3].

Underground coal gasification has some environmental benefits relative to conventional mining including no discharge of tailings, reduced sulfur emissions and reduced discharge of ash, mercury and tar and the additional benefits of CCS [4]. Atmospheric CO_2 is a major greenhouse gas concern in fossil fuel processes. Due to global climate change, CCS is an important technology that can be combined with UCG Carbon capture and sequestration is the process to remove the store greenhouse gases from resulting process streams to reduce buildup of these gases in the atmosphere [5].

1.4. The uses of the UCG product gas

The main uses of the UCG product gas are

1.4.1. Fuel gas used for electricity generation

The UCG operation is optimized to produce a high calorific value product gas for this purpose. The gas turbine (simple or

Table 2
List of quantitative and qualitative environmental indicators.

Technology (Levelized unit electricity cost $/MWh)	Co_2 emission t/GWh	NOx emissions kg/GWh	SO_2 emissions kg/GWh	Footprint m²/GWh	Magnitude of disturbance (qual.)	Water consumption (qual.)	Water/ground water impacts (qual.)	Long term unknowns/ liabilities (qual.)	Worst case scenario (qual.)
Energy efficiency (application dependent)	0	0	0	Low	Low	Low	Low	Low	Low
Large scale wind (80–108 $/MWh)	17	35	35	1576	Low	Low	Low	Low	Low
Solar PV (roof) (160–800 $/MWh)	59	248	512	41	Low	Low	Low	Low	Low
Hydro (run of river) (50–180 $/MWh)	Low	Low	Low	Low	Low	Low	Low	Low	Low
Biomass (waste) (47–66 $/MWh)	Low	Variable	Variable	Low	Low	Med	Low	Low	Low
Natural gas cogeneration (55–86 $/MWh)	427	802	311	263	Med	Med	Low	Low	Med
Natural gas combined cycle (55–86 $/MWh)	534	1504	584	329	Med	Med	Low	Low	Med
UCG with CCS (48.5–87 $/MWh)	330	280	60	99	Med	Med	High	High	High
Coal with CCS (113–114 $/MWh)	197	888	65	434	High	Med	Med	Med	High
IGCC (40 $/MWh)	800	410	70	434	High	Med	Low	Low	Med
Pulverized supercritical coal (39–56 $/MWh)	986	2247	2581	434	High	Med	Low	Low	Med

combined cycle) and boiler plant (alone or as supplementary fuel) can be used for power generation [6].

1.4.2. Syngas for synthesis of chemicals or liquid fuels

The conditions in UCG operation may be manipulated to produce high hydrogen content in the product gas typically a H_2: CO ratio of 2:1 is optimal. The Syngas is used for the manufacture of crude oil equivalents (diesel, naphtha and wax) other liquid fuels (DME and methanol) ammonia and methane [6].

The gas obtained by UCG of low grade coal has mostly been used for power generation in the past. The gas product at Angrensikaya [7] and Chinchilla [8] are used for power generation. The Chinchilla UCG-IGCC project is designed for maximum power generation, output of this project as given in Table 1. The byproduct along with power generation favors the economics of the project. UCG operation in Chinchilla is the longest in duration and the largest outside Russia the UCG technology was provided to Linc Energy by Ergo Inc. (Canada) and originated from the former USSR [8].

1.5. Economics of UCG for power generation

A 100 MW power plant with coal having a GCV of 3300 kcal/kg was chosen for a case study. The coal seam thickness was assumed to be 2 m [9]. The following conclusions were reached based on cost estimations using available data; the capital cost for IGCC is estimated as Rs. 8500 millions, and for UCG as Rs. 6400 millions. In case of IGCC this is attributed mainly to the additional cost of the specially designed gasifier, and coal and ash handling. However, the cost of generation (Rs. /KWh) is higher in case of UCG (Rs. 3.6/KWh) as compared to IGCC (Rs. 2.6/kWh). This is mainly due to the higher fuel cost and lower gross efficiency associated with UCG. Finally, it has been mentioned that COG in case of UCG will be comparable to that for IGCC if the seam thickness is greater than 2 m and the calorific value of the coal is above 3300 kcal/kg [9].

1.6. Environmental concerns of UCG technology

1.6.1. CO_2 emission and carbon capture and storage (CCS)

UCG with electricity generation will likely result in Green House Gases (GHG) emissions 25% lower than conventional coal electricity generation [10]. UCG can also integrates CCS, where carbon dioxide(CO_2) is captured and then transported via pipeline and either sequestered or used to enhance oil recovery, into its operation to achieve more significant GHG emissions reductions. As shown in Table 2 current CCS cost indicate that integrating CCS into UCG operations will be less costly in comparison with other electricity-generating technologies because capturing the CO_2 stream is easier and does not require the same capital investments as other technologies [10].

1.6.2. Ground subsidence

UCG creates cavities underground similar to other long wall underground mining activities. Eventually the rock and other material that are no longer supported by the coal that the UCG process has removed will fill the cavities. Subsidence is manageable and when managed properly, has resulted in minimal local impact. Subsidence is also not unique to this technology and is common for conventional underground mining.

1.6.3. Air emissions

The combustion of Syngas, like the combustion of natural gas, will generate air emission with associated environmental and health concerns like acid rain. However, the emission of air contaminants such as sulfur dioxide, nitrogen oxides and particulate matter per unit electricity are expected to be significantly lower than a conventional coal power plant.

Nonetheless, air emission concerns will depend on the combined sources of emissions in the region and pollution control standard to which the facility is designed.

1.6.4. Ground water

Ground water contamination is considered “the most significant (environmental) risk related to UCG [11]”. The gasification process creates a number of compounds in the coal seam including phenols and polycyclic aromatic hydrocarbons, benzene, carbon dioxide, ammonia and sulfide [11]. These compounds can migrate from the gasification zone and contaminate surrounding ground water. For example, studies in the Soviet Union in the 1960 revealed that UCG could result in widespread ground water contamination [1]. Looking at the broader context, most UCG operations have not produced any significant environmental consequences [4]. For example, European trials were completed with no environmental contamination detected during operation or within five years after operation [1]. Similarly a UCG test site in Chinchilla, Australia did not result in ground water contamination [4].

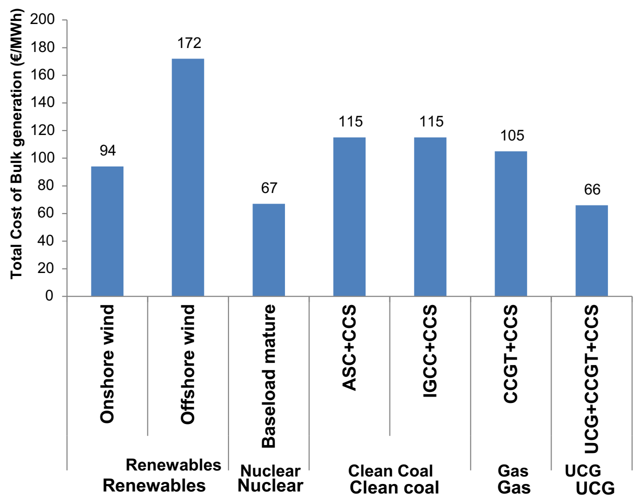
1.6.5. Ground water contamination: incidents reported in UCG

1.6.5.1. Hoe Creek test in Wyoming. In the United States, a number of the tests concentrated on the determination of the environmental impact, particularly on groundwater, of which the Hoe Creek test in Wyoming is one of the best documented. Here the tests were carried out at shallow depths (55 m) and, at the Hoe Creek 2 and 3 sites, the UCG experiments were carried out at high pressures. This resulted in product gases containing phenols and condensable hydrocarbons escaping into the overlying water-bearing units. In addition, groundwater re-entered the burn areas after the test, and came into contact with condensed coal tars and became contaminated with organic materials. Local groundwater flow carried contaminants down-gradient to the east and south. In then Hoe Creek 1 burn, where high induced pressures were not used, elevated levels of contaminants were not encountered, indicating this had an important control on groundwater.

The Rocky Mountain 1 (RM1) UGC test at Hanna, Wyoming, involved extensive site characterization, instrumentation and monitoring in order to gain a detailed understanding of the environmental and hydrogeological variables. Following the test venting, flushing and cooling of the cavities was carried out to reduce groundwater contamination [12]. The results of this test proved that UCG can be conducted in an environmentally benign manner, but that ground water quality and aquifer head were impacted locally at the test site [13,14]. The El Tremedal trial in Spain used the knowledge gained from such earlier UCG experiments and here underground conditions were kept as close to hydrostatic pressure as possible. As a result no pollutants were detected apart from hydrogen sulfide, which had been predicted.

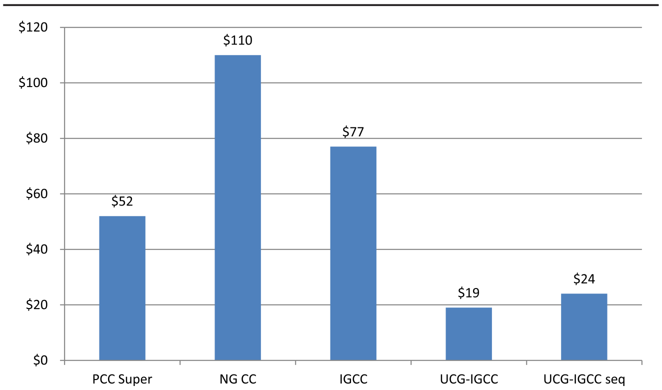
1.6.5.2. Kingaroy project blocked. On 15 July 2010 the Queensland Department of Environment and Resource Management (DERM) announced by media release the forced cessation of operations on the site. On 17 July 2010 DERM served an Environmental Protection Order on Cougar Energy which halted the development of the Kingaroy project. The decision followed the detection in May 2010 of traces of benzene slightly above the prescribed reporting trigger levels in two samples from a single monitoring bore near the plant on Cougar Energy's leasehold. The reporting trigger levels are set for monitoring and reporting detections of specified chemicals to the Queensland Government. They do not

Table 3
Comparision of UCG with other power producing technologies.
Source: http://narasimhancs.com/2012/11/08/clean-coal-technologies.



Notes: ASC = Advanced supercritical, CCGT = Combined-cycle gas turbine, CCS = Carbon capture and storage, IGCC = integrated gasification combined cycle.

Table 4
Cost of electricity.



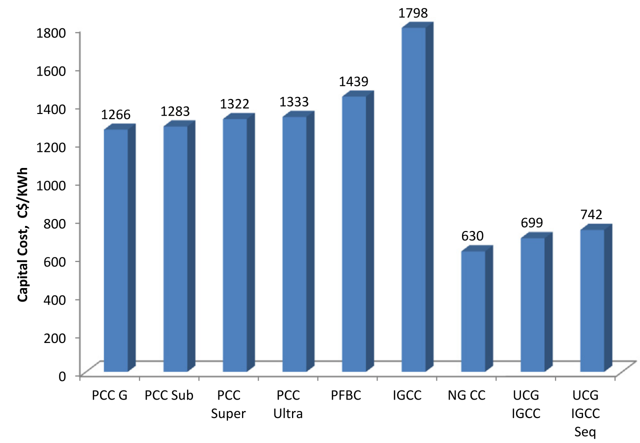
signify occurrences of environmental harm. In both instances, 2 ppb of benzene were detected, against the reporting trigger level guideline of 1 ppb [15].

These were the only two such instances reported from more than 530 independent tests of monitoring bores on the site and in surrounding landowners′ properties since March 2010. Monitoring and testing of bores on the site and at landowners′ properties continues. This reinforces Cougar Energy′s belief that the two benzene detections were isolated and transitory readings and had not caused environmental harm.

Queensland Government tests also confirmed that there were no concerns with water quality in the monitoring bores and there was no evidence to indicate that the Project presented any danger to human health or local farming activities.

Despite this, on 28 January 2011, the DERM served a Notice of Proposed Action on Cougar Energy, proposing to restrict activities at Kingaroy to decommissioning, rehabilitation and care and maintenance. The Company lodged a submission on 28 February 2011 contesting the proposed orders citing numerous incorrect assertions by DERM. However, on 31 August 2011, after an internal review DERM confirmed its original decision to amend Cougar Energy′s Environmental Authority to prevent development of the

Table 5
Capital cost of new power plants, Canada.
Source: **Courtesy of Ergo exergy**



Project. Cougar Energy is presently appealing this decision in the Queensland Planning and Environment Court.

Cougar Energy believes that it has been unfairly penalized by DERM. The miniscule, transient and isolated benzene readings at the site did not pose any danger to the local community and they are significantly lower than those reported at Coal Seam Gas projects in Queensland which the Government has allowed to proceed. As a result of this decision Queenslanders currently have been denied a cleaner and more cost competitive source of electricity at a time when the State is forecast to suffer a growing shortfall in reserves of base load power from 2013 to 14 [15].

1.7. Comparison of UCG with conventional coal mining techniques

The environmental concerns associated with UCG processing are no worse than those associated with winning coal by underground or surface mining followed by gasification in a surface Gasifier. In both cases, the wining of coal from underground will result in some subsidence and its accompanying problems. Indeed, in situ processing of coal can be a significant improvement over some aspects of surface processing. For example, the steps usually followed for surface extraction and recovery include:

i. Mining of the coal,
ii. Cleaning the coal in a coal preparation plant,
iii. Transporting the coal to the point of use,
iv. Storing the coal,
v. Preparing the coal for use, and finally
vi. Combusting, gasifying or liquefying the coal.

Each of these steps provide a variety of solid, liquid, and gas residues that must be treated prior to disposal. In addition, a significant amount of portable water is consumed, and this water has to be treated before it can be returned to the environment. UCG, on the other hand, offers the potential to combine several steps such as mining, cleaning, preparation and processing into a single operation which may well be acceptable environmentally and in addition, offers the potential of reduced costs relative to the total costs associated with surface processing (Table 3).

1.8. Comparision of UCG with other power producing technologies

UCG is the lowest cost power generation technique than all other power producing technologies as shown in Table 4, power generation cost for (UCG + CCGT + CCS) is €66 per MWh, where as

the power generation cost for Combined-cycle gas turbine + CSS, clean coal nuclear and renewable are €105, €115, €67 and €172 per MWh respectively. Table 5 provides us comparison of the capital cost of new power plants in Canadian dollar, which shows that UCG-IGCC (C$ 699) and UCG-IGCC-CCS(C$ 742) are in good competition to the NG-IGCC (C$ 630).

1.9. Clean cavern concept

A possible additional environmental problem with UCG is the risk of contaminating the groundwater system. Early UCG tests, which resulted in contaminated groundwater in the un-reacted coal as well as in adjacent water bearing zones, were performed with high cavity pressures to inhibit excessive water influx into gasification reactor. Subsequent laboratory tests led to the conclusion that high cavity pressures have little effect on the quantity of water influx into the reactor during gasification operations. As a result of the laboratory studies and modeling of the generation of ground water contaminants, a procedure (clean cavern concept) was formulated to minimize groundwater contamination during and immediately following UCG operations. In this concept, the subsurface reactor pressure is maintained below hydrostatic to minimize the loss of organic laden gases and to ensure a small but continuous influx of ground water into gasification cavity. When the gasification operations are complete, steam is then injected into the cavity to promote the rapid cooling of the cavity walls and residues, and to “strip” the soluble and volatile organics from cavity. The steam and contaminated gases are routed through an incinerator before being exhausted to the atmosphere. Operating in this fashion has confined the contaminants from UCG to the gasification cavity, and the contaminated cavity water can then be pumped to the surface for treatment before it spreads to surrounding ground water system.

1.10. Pakistan energy policy

1.10.1. Integrated energy plan 2009–2022

Pakistan's total primary energy demand is expected to increase from 62.9 MMTOEs in 2008 to 122.46 million TOEs in 2022. During 1992–2008 primary energy requirements of the country increased at an annual average growth rate of 5%. Natural gas remains a dominant fuel in 2008 providing 47.5% of the current energy mix it will be reduced to 28% by 2022 out of which 7% will be through imports. The oil (i.e. petroleum products) share in total primary energy demand is expected to decline from 30.5% in 2008 to 20%. Coal's share in the total primary energy requirements is expected to increase from 9.2% in 2008 to around 15% by 2022 [16]. It may be mentioned that the Government as part of development of indigenous energy resource base is aiming to increase Coal's share significantly as the country has large reserves of coal at Lakhra (1.3 billion metric tons), Sonda (7.1 billion metric tons) and Thar (175.5 billion metric tons). However on ground progress with respect to the development of infrastructure and mining has been very slow. This needs to be changed through the creation of an integrated coal policy which will encourage the development of the mining infrastructure while simultaneously ensuring support infrastructure viz; roads, water supply is all developed in tandem with the set up of power generation facilities.

Since the mining infrastructure may take longer to develop it is visualized that coal fired power generation may commence sooner through imported and then once the infrastructure has been built to switch to local coal. There is also an important shift that must occur. There is plenty of coal in Baluchistan, Sindh and Punjab which has less problems in its mining and infrastructure. If proper industrial mining could be developed this could provide better quality coal feedstock to local coal based power projects.

Hydel, the cheapest source of energy is currently contributing to the extent of 10.9% in country's energy mix. Its share will increase to 20% by 2022. It may be mentioned that the increase in hydel share/growth will be primarily dependent upon construction of dams as per considered time frame. These dams have been identified and site studies are at various stages of development. It is imperative that financial and technical resources be brought to bear on these projects in a prioritized fashion without allowing the development of these projects to be politicized [16].

The share of nuclear will go from 1% to 3%. In order to ensure that Pakistan can increase the nuclear sectors modest contribution, a great deal of effort needs to be given to indigenizing the production of fuel rods and to power plant manufacturing. The share of Alternative and Renewable energy will be increased aggressively to 12% of the total Energy Mix through roll out of Run of the River – Micro Hydels, Wind farms Onshore and Offshore, Off-line Solar and by introduction of local Bio-Diesel and Ethanol production. The lowest hanging fruit is Ethanol which could be blended immediately in the local oil industry. This must be done without throwing out the existing refining sector off balance through introduction of Ethanol blending. Through the creation of a more level playing field between competing fuels Ethanol and Bio Diesel could be introduced and indigenous resources could be utilized. Wind and solar energy in the mid-term should be encouraged in those areas where these resources exist [16].

1.10.2. Federal government new energy policy 2013

The federal government has prepared a new energy policy, which aims at increasing power generation up to 26,800 MW and decreasing average power generation cost per unit from Rs 14.67 to Rs 10.00 per unit in three years, Geo News reported.

Sources add that a final presentation on energy policy will be presented to Prime Minister Nawaz Sharif on June 27th and in the Council of Common Interest (CCI) meeting on July 29 the provinces will be taken into confidence; following this the prime minister will announce the new energy policy [17].

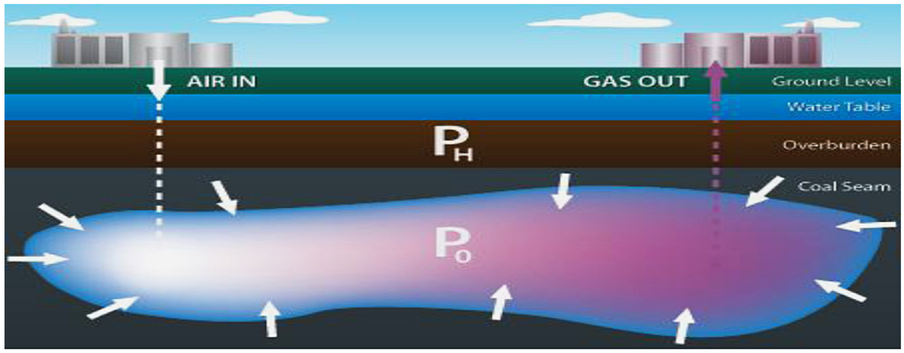
Under the new energy policy power production from the existing 12,200 MW will be boosted up to 26,800 MW, while the power production cost will be reduced by 30 percent on average and efforts will be made to zero the load shedding.

The four key-points of energy policy include: Bridging the difference between the demand and supply of energy, ensuring cheap electricity to the consumers, minimizing power thefts and making the energy sector attractive for investments [17].

1.10.3. Importance of UCG technology for Pakistan

Pakistan's coal resource potential is estimated to be around 186 billion tonnes out of which 175 billion tonnes are found in Thar — one of the largest lignite deposit in the world and has the capacity to meet energy requirements of the country for decades. In pursuing clean coal technology The Planning Commission, Government of Pakistan has approved UCG Project Block-V as a R&D Project and engaged Pakistan's renowned scientist Dr. Samar Mubarakmand to develop a local technology and execute the Pilot Project. The Project is for production of Syngas from Thar and establishment of UCG based Power Plant of 100 MW. Test Burn was ignited on 11th December, 2011 [18]. The TCEB in its 14th meeting deiced that for 100 MW Power Plant, an International Expression of Interest should be floated by PPIB&TCEB. Based on the technical and commercial data provided by Dr. Samar Mubarakmand, EOI is being developed.

After the successful demonstration of UCG pilot project, UCG will be the technology of prime interest in Pakistan for utilization



P_H = Hydrostatic Pressure; P_O = Operating Pressure in the gasification chamber.

Fig. 2. Showing hydrostatic pressure vs. operating gas chamber pressure.

of coal for power generation as compared to conventional coal mining techniques, due to its environmental friendly nature [18].

2. Practical consideration of environmental concerns in UCG

2.1. Site selection

Appropriate site selection is the most important mitigation measure and is essential to minimize potential groundwater contamination. Operators should ensure the site is well characterized and that the coal seam has limited connectivity with other water sources [11].

2.2. Operational practices

There are inherent aspects of UCG that help to reduce the contamination potential of UCG projects. During operation, a steam barrier or “steam jacket” is created that surrounds and contains the process and leakage [4]. Operators should maintain the gasification chamber below hydrostatic pressure in the surrounding aquifer to ensure that all groundwater flow in the area is directed inward, towards the gasification chamber as shown in Fig. 2 [12]. UCG operators must also invest in groundwater monitoring around the facility to ensure contaminants are not migrating from the gasification chamber.

2.3. Abandonment practices

The appropriate shutdown process is a controlled shut down in which the gasification zone is allowed to cool slowly. During this time, the operator should continue extracting gas until the gasification process stops completely. In this way contaminants can be evacuated out of the gasification zone before the site is abandoned. Operators should also monitor groundwater for contaminants for a period of time after the site is abandoned. The actual duration of monitoring will depend of the specific site.

2.4. Subsidence

Subsidence is the sinking or lowering of a surface region relative to the surrounding region. It occurs as a result of the removal of material from the underground coal formation. In general, UCG subsidence results in height decrease equivalent to one-third of the vertical thickness of coal seam and would affect only land directly above the gasified coal seam. The magnitude and characteristics of subsidence depends on many factors including seam depth, rock stiffness and yield strength, disposition of seam, the stress resulting from gasification, and other geological properties [4]. Subsidence typically results in a uniform lowering of a region as opposed to abrupt path holes [1].

In general, subsidence appears to be a site specific issue. With proper site selection and operational; management, it should be possible to avoid significant impacts to surface water, road and industry infrastructure and buildings by avoiding regions most sensitive to surface level changes.

2.5. Pollution-free UCG: The Triple Lock Mechanism

The Triple Lock Mechanism results in the formation of a Pressure arch that block the movement of particulates outside the pressure arch.

This Mechanism based upon three main steps as shown in Fig. 3

(a) Hydrodynamic trapping
Hydrodynamic Trapping involves extremely slow groundwater movement at depths of hundreds of meters.

(b) Pressure-arch trapping
This step involves same theory as above mention by Younger and Adams that the UCG process induces development of a low-permeability zone beyond the immediate zone of stratal caving.

(c) Geochemical trapping
This step involves the irreversible sorption, mineralization and biotransformation limits transport of pollutants to <30 m (even if flow regime would permit this).
This step can be justified by using the general UCG site Selection Criteria [19] which is providing the guideline for site selection and mentioning minimum distance of up laid aquifer must be more than 31 m above the UCG cavity Zone. That will eliminate the chances of Ground water contamination through geochemical trapping mechanism. So as a result of all above steps pollutants would be triply locked-in within the cavity of former UCG burn zone. So there will be no chance of Ground water contamination.

2.6. CO_2 Emissions and carbon capture and sequestration

UCG combined with power generation is expected to be 25% less green house gas intensive on a per MWh basis then a super critical coal plant when both are operated without post-combustion carbon capture and storage (CCS) [20,21]. However, real potential of UCG is that it produces syngas that is amenable to pre-combustion carbon capture [22]. UCG offers a CO_2 stream that will have a capture cost estimated in range of $ 50 to $ 110 per ton of CO_2. More generally, most suitable for UCG are usually near potential sequestration sites Fig. 4. A study of North American

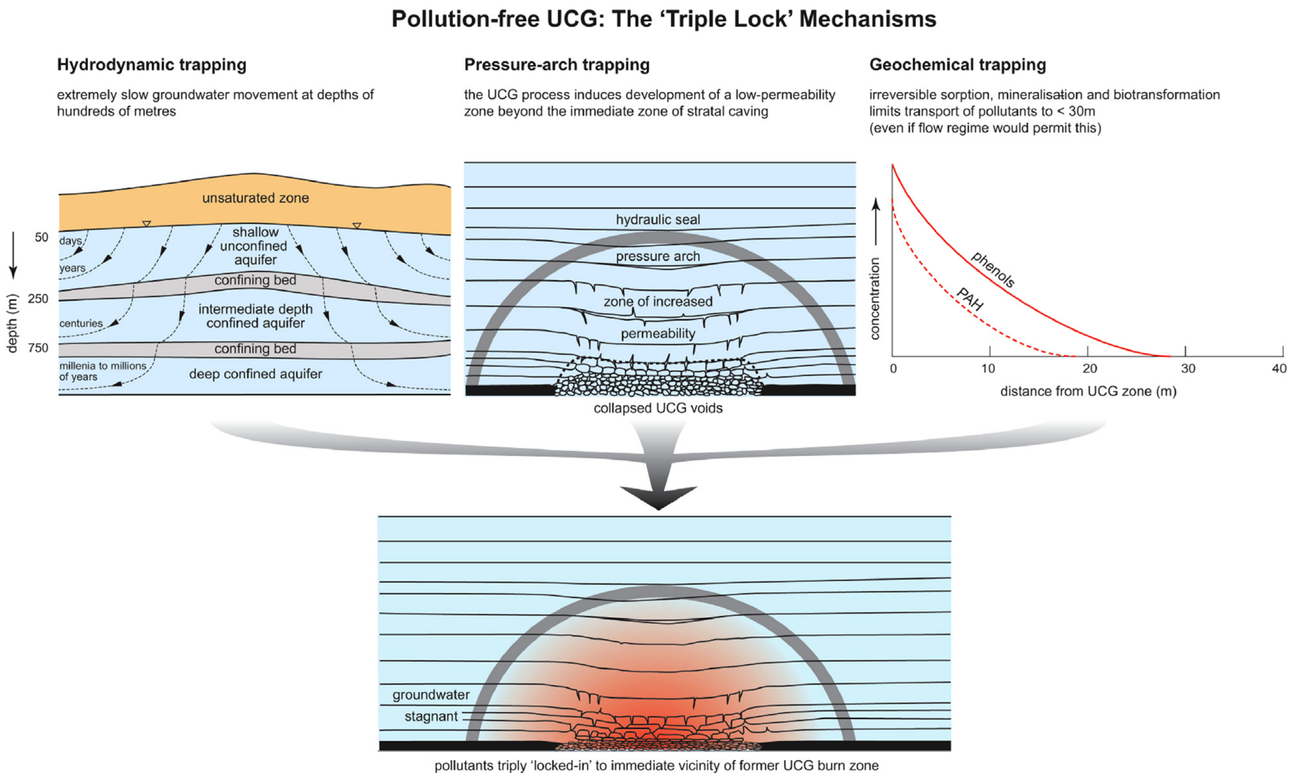


Fig. 3. Triple lock mechanism.

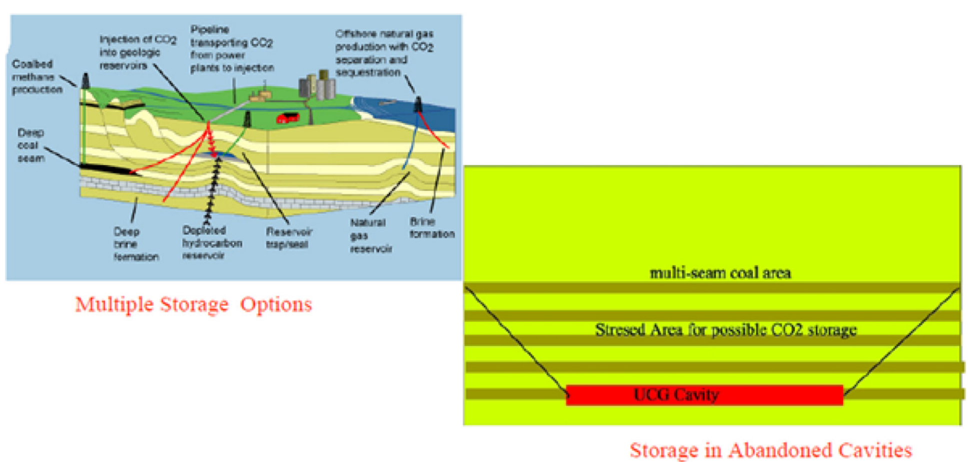


Fig. 4. CO_2 emission and capturing.

previous, current or planned UCG pilots found that more than 75% of the projects were within 50 km of potential saline aquifers, depleted oil and gas fields and EOR schemes [23].

2.7. Operational control

The pressure in the underground gasification zone is primarily controlled by the rate of air/oxygen injection and the corresponding rate of extraction. A difference between these two rates allows the operator the ability to vary the pressure. The directional travel of UCG operation along a coal seam also is controlled. This is accomplished by strategically locating the injection and extraction wells. Once two wells are interconnected, the negative pressure created as gas leave the extraction well will draw the gasification reaction toward the exit well.

2.8. Air quality

UCG will clean the Syngas at surface facilities near the UCG site to reduce air emissions. The cleaned gas then will be transported via pipeline to the power generation facility. With UCG, there are essentially two categories of non-GHG air emission: criteria air contaminants (e.g., nitrogen oxides, sulfur dioxide and particulate matter) and volatile trace elements (e.g., mercury, arsenic and selenium) [24,25].

UCG plans to use traditional gas cleaning technologies like acid gas removal for H_2S and bag houses for PM removal to reduce air emissions to within regulated limits.

UCG offers some inherent air emission benefits to conventional coal. During UCG, a significant portion of volatile trace elements like mercury, arsenic and selenium as well as sulfur remain in the underground cavity. In coal combustion, these compounds must

Table 6
Water quality of shallow aquifer.

Parameters	Unit	WHO	Results
pH	–	6.5–8.5	7.78
EC	ms/cm	–	8060
Sodium	mg/l	–	125
Magnesium	mg/l	–	140
Calcium	mg/l	–	230
Chloride	mg/l	250	191
Bicarbonate	mg/l	–	185
Silica dioxide	mg/l	–	0.10
Total hardness	mg/l	–	370
TDS	mg/l	1000	4030
Turbidity	NTU	< 5	0.77

be recovered from the flu gas at relatively higher cost. Combustion of Syngas should also result in fewer NO_X emissions because the combustion occurs at lower temperature than coal combustion [1].

2.9. Land use impacts

While UCG pilot project will have a minimal number of wells drilled during operation, the commercial scale will occupy approximately two to three sections (one section = 2.6 km^2) of land over a life time and will include a few hundred wells spaced 30 to 100 m apart. The 300 MW commercial facilities are anticipated to operate for 30 years. UCG operations progress along the coal seam exhausting one panel (300 m across) before starting a new one.

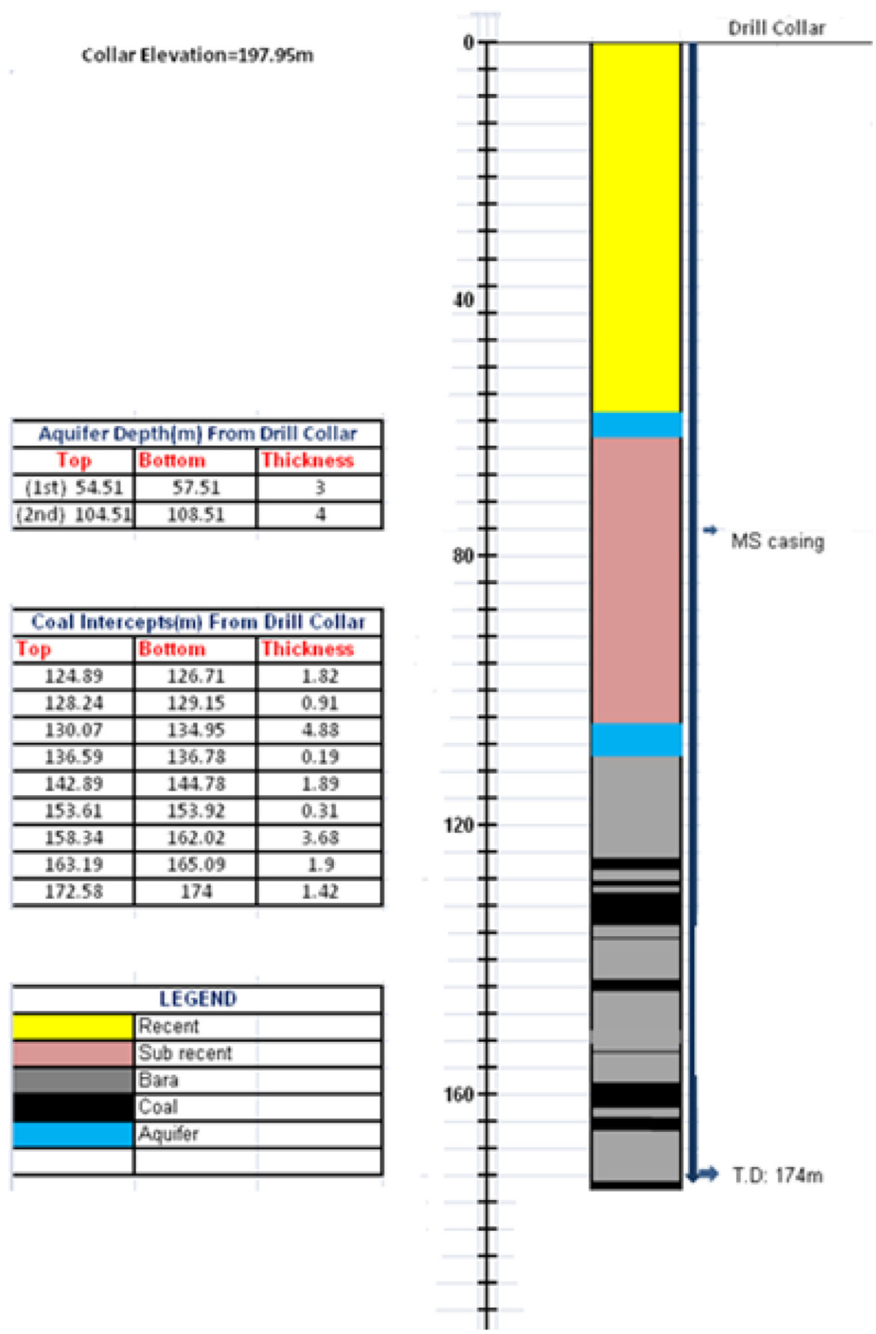


Fig. 5. Litholog of well bore.

Table 7
Water quality of deep aquifers.

Parameters	Unit	WHO	Results
pH	–	6.5–8.5	7.14
EC	MS/cm	–	10,170
Sodium	mg/l	–	177
Magnesium	mg/l	–	410
Calcium	mg/l		440
Chloride	mg/l	250	450
Bicarbonate	mg/l	–	815
Silica dioxide	mg/l	–	4.8
Total hardness	mg/l	–	580
TDS	mg/l	1000	5080
Turbidity	NTU	< 5	37.2

At any given time the operation will actively disturb approximately one half-section, while the previous regions that no longer have active operations will be progressively reclaimed as needed.

3. Results and discussion

3.1. Environmental concerns and monitoring in UCG Thar coal project

3.1.1. Hydrology of block-5 and groundwater contamination aspect

The water resources of the Thar Coal field can be divided in two categories

(a) Shallow water aquifer: used for domestic use in Local communities.
(b) Deep water aquifer: Highly brackish range.

3.1.1.1. Shallow water aquifer: used for domestic use in local communities. The communities residing in the Thar area rely on rainfall and groundwater aquifers to meet their water needs. As the evaporation rate is high, so a very little moisture is retained in the soil. There are no perennial surface flows and hence no system of natural drainage lines and streams is found in the Thar region. Rainwater either seeps through the soil or flows to the nearest *dhand* or playa where it accumulates and is used by the community while it lasts.

Water for domestic use acquired from wells tapping the rain-fed top or quaternary aquifer. The thickness of the top aquifer varies between 4 m and 18 m and the aquifers are 30 m and 80 m below the ground level. The monsoon rain feeding the aquifer occurs from July to September. By February or March, the shallower parts of the aquifer get depleted and the well became saline. The water quality parameters of shallow aquifier are given in Table 6.

3.1.1.2. Deep water aquifer: highly brackish range. According to Litho-log (Fig. 5) of well bore it is obvious that there are two aquifers present above the coal seams of Thar coal block–5 and one underneath the coal seams. The 1st aquifer lies at 180–192 ft (55–59 m) depth. 2nd aquifer ranges from (105 to 109 m) 344 to 358 ft. The third aquifer is laid below the extractable coal seams at an average depth of 195–250 m (640–820 ft). The local communities use the dug wells for drinking water purposes that rely on 1st aquifer with depth range 180–192 ft (55–59 m), while the coal seam of UCG interest lies at depth of 520–590 ft (158.5–180 m). So the 1st aquifer used for portable water of local communities is situated at 328 ft (100 m) above the area of

Table 8
Results of organic pollutants in ground water samples.

Parameter	Results (ppm)								
	WHO safe limits	**MIJ-1**	**MIJ-2**	**MIJ-3**	**MIJ-4**	**MIJ-5**	**MIJ-6**	**MIJ-7**	**MIJ-8**
Benzene	**0.01**	**ND**	**ND**	**0.01**	**ND**	**0.01**	**ND**	**ND**	**ND**
Toluene	**0.7**	**ND**	**ND**	**0.02**	**ND**	**0.013**	**0.02**	**ND**	**ND**
Ethyl benzene	**0.3**	**ND**	**ND**	**ND**	**ND**	**0.01**	**ND**	**ND**	**ND**
Xylene	**0.5**	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**

expect UCG reactor. Therefore there is no chance of water contamination of potable water aquifer in the project area. Similarly 2nd aquifer is laid at 162 ft (49 m) elevation to the targeted coal seams. So it is also in the safe range of height.

In considering the water quality of 2nd and 3rd water aquifers of the project area with TDS range of 6000–10,000 ppm (as given in Table 7) that is brackish water with respect to quality due to which both of the aquifers are exempted from drinking regulation of EPA.

3.1.2. Results of ground water monitoring after test burn

Water samples from the dug wells of local communities as well as from observation of UCG Grid area were collected regularly and tested for the organic pollutants like Phenol, Benzene, Ethyl Benzene, Toluene, and Xylene. But due to controlled operational practices adopted during the test burn the risk of contamination was eliminate. As it is cleared according to the Table 8 showing the results of these parameters within the water samples all the parameters stands within the safe limit of WHO for drinking water guidance.

3.2. Subsidence

The sinking or lowering of a surface region relative to surrounding region occurs in UCG as a result of the removal of material from underground coal formation. Leftover solid waste after gasification shall remain underground filling in the gasified area. Mudstone of coal seam roof is consolidated after high temperature sintering. Besides, there will be coking layer on the top of the gasification channel, which will move upward along with the upward movement of Gasifier. In the end of gasification after cooling, there will form a coking ring at the top of gasification area, which proves by experiment to be 5–8 times stronger than common bricks. Therefore the ground surface subsidence of UCG gasification is less than that of mechanical coal mining.

In case of test burn at UCG Thar coal project the subsidence was not observed the problem of subsidence was solved through the design of the UCG grid by managing well spacing of 25 m of two adjacent wells. This well space was designed by keeping in view the geology of overburden. By using the well spacing as per design the risk of subsidence was eliminated in the UCG Thar Coal Project.

3.3. Purification of product gas

The UCG Syngas comes out of the production well at a flow rate of 20,000 Nm^3/hr at 2 bar (absolute) pressure and 300 °C temperature (max). The raw product gas may contain some quantity of dust (100–200 ppm by weight). Total hydrocarbon ($\leq$ 20 gm/Nm^3) Tar ($\leq$ 1 gm/Nm/3), CH_4 (1–2%), and contain 0.4 kg water content/kg of gas at 2 bar (a) and 300 °C. The particle size is expected to be in the range of 5–10 μm the composition of raw Syngas is shown in Table 9, these contaminants, sulfur and moisture if not removed

Table 9
The raw Syngas composition as follow at 2 bar and 300 °C.

Syngas components	Composition
H_2	(15–20%)
CO	(10–15%)
CO_2	(20–25%)
N_2	(40–60%)
H_2S	(1%)
H_2O	(0.4 kg of water/kg of Syngas)
Total Hydrocarbon	(< 20 mg/Nm³)
Tar	(< 1 mg/Nm³)
CH_2	(1–2%)

Table 10
Product gas specification after purification.

Syngas components	Composition
Particulate content	≤ 50 mg/Nm³
Moisture content	≤ 50 mg/Nm³
Tar content	≤ 50 mg/Nm³
H_2S	≤ 50 mg/Nm³
NH_3	≤ 20 mg/Nm³
Impurity grain size	≤ 5 μm
Impurity contents	≤ 30 mg/Nm³
Product gas temperature	< 40 °C
H_2	(15–20%)
CO	(10–15%)
CO_2	(20–25%)
CH_4	(1–2%)

may badly affect the generator operation resulting in frequent maintenance and loss of capacity especially at ambient temperature approaching the dew points of moisture and hydrocarbons the gas therefore needs to be cleaned desulfurized and dehydrated to a product gas at temperature less than 40 °C, containing H_2S (≤ 50 mg/Nm³), NH_3 (≤ 20 mg/Nm³), tar contents (≤ 50 mg/Nm^3), impurity grain size (≤ 5 μm), impurity content (≤ 30 mg/Nm^3) and moisture content (≤ 100 mg/Nm³) the purified Syngas composition is shown in Table 10.

3.4. CO_2 capturing and sequestration

Carbon dioxide will be separated from Syngas using Gas purification plant and will be compressed and re injected into empty coal cavity of the test burn reactor. Main stream of the product gas contains CO_2 that will be separated pre-combustion through the main stream using Gas purification plant. After the power generation the post-combustion CO_2 will evolve that would be compressed and both types of CO_2 will be sequestered using the empty cavity of test burn that is the most useful feature of the empty cavity of the UCG reactor.

4. Conclusion

UCG is gaining interest due to its low capital cost as compared to conventional coal mining techniques. UCG can be concluded as "the clean coal technology" by capturing pre-burn and post-burn carbon dioxide. Pre-burn capture of carbon dioxide, hydrogen sulfide, nitrogen oxides, tar and particulate matters including coal ash can be captured by passing the product gas through gas purification plant. Post-burn CO_2 capture can be achieved by coupling UCG with CCS. The UCG as compared to other coal mining techniques has lowest rate of human accidents, lowest land use and surface impacts and lowest disturbance to the ecology of project area. Therefore, it is known as environment friendly technology for coal exploitation. This is the technology through which we can use the reserves of Thar coal fields to change the energy scenario of Pakistan.

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